High Radiation Tolerance of InP-based Resonant Tunneling Diodes

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(Proceedings of the Nanospace '98 conference, Nov 1-6, 1998, Houston, TX)

Abstract

We have fabricated arrays of 100 and 1000 resonant tunneling diodes based on InP substrates for exposure at room temperature with fluences of 3 MeV protons up to 7×10^{14} H^+/cm^2. Proton fluences below about $1 \times 10^{13}/cm^2$ have little effect on the RTDs, but at higher fluences radiation damage causes the peak current to decrease and the valley current to increase. The radiation tolerance of the RTDs is compared to that of InGaAs photodiodes and found to be orders of magnitude more tolerant. This is the first time that radiation-effects have been studied in this type of device.

Introduction

Indium phosphide (InP) based resonant tunneling diodes (RTDs) are the fastest semiconductor switching devices, with demonstrated large signal switching speeds as high as 300 mV/ps and switching times as short as 1.5 ps.[1] These devices in combination with InP-based high electron mobility transistors (HEMTs) significantly enhance circuit performance and are now being developed for use in systems with 10 - 100 GHz data rates.[2] The combination of high speed, lower power and small size makes RTD/transistor circuits attractive for space applications.

In order to be useful in satellite applications, however, electronic devices must tolerate the radiation environment of earth's geomagnetic fields. Hence before deployment, it is important to determine specific vulnerabilities to radiation damage that this new technology may possess. Measuring radiation-tolerance has the added benefit of revealing information about the perturbative effect of disorder on the operating parameters of solid state devices, and can result in fabrication techniques for improving device uniformity and increasing radiation hardness, as well as enhancing understanding of the physics of device operation.

The effect of exposure of InP-based AlAs/InGaAs RTDs to a space radiation environment was simulated using 3 MeV protons generated in NRL's Pelletron accelerator. Changes in device operating parameters were measured as precisely controlled amounts of disorder were introduced into the RTDs. The results are reported here.

Experimental

The films used in fabricating the RTDs were grown by metalorganic molecular beam epitaxy (MBE). The RTDs are based on an AlAs/InGaAs/InAs/InGaAs/AlAs structure approximately 10 nm thick, with an AlInAs layer to reduce the peak current density to approximately 5 A/cm^2.[3] Each device has a low current n$^+$ InGaAs contact layer above and below the RTD. Two arrays of devices were tested. The first array, called R1, consisted of 100 1x1 µm RTDs connected in parallel. The second array, called R2, contained 1000 0.4x0.4 µm RTDs connected in parallel.

Current-Voltage (IV) curves were measured using an HP-4155A semiconductor parameter analyzer. The RTD arrays displayed n-shaped IV curves typical of this kind of bistable device. Five variables were determined from each IV curve, namely the current and voltage at the tunneling transmission peak, I_p and V_p; the current and voltage at the transmission minimum, I_v and V_v; and I_p/I_v, the peak-to-valley current ratio.

Irradiations were performed at room temperature in a tandem Van de Graaf accelerator, using 3 MeV protons incident 7^o from the surface normal to discourage ion channeling effects. Protons of this energy traverse the RTDs without significant energy loss, so the damage profile through the devices was uniform. Disorder caused by 3 MeV protons consists mostly of point defects such as vacancies and interstitials, but in addition is expected to include a fraction of small defect clusters.

In a typical experiment, the IV curve of an array was measured, the array was irradiated with an incremental fluence Φ, and the procedure was repeated. Following the last irradiation, IV curves were measured periodically for seven weeks in order to investigate annealing at room temperature.

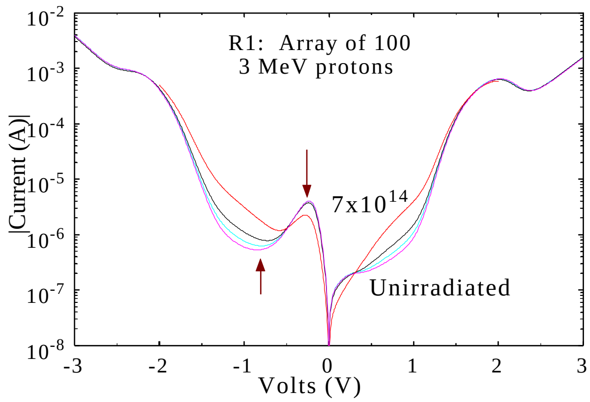

Fig. 1. IV curves for irradiations at room temperature and proton fluences up to $7x10^{14}$ H^+/cm^2. Arrows indicate peak and valley positions.

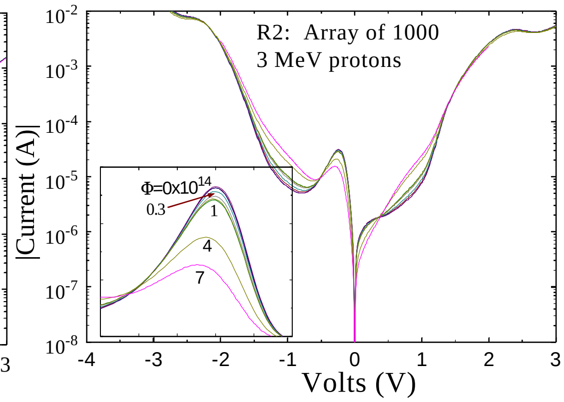

Fig. 2. IV curves for irradiations at room temperature and proton fluences to $7x10^{14}$ H^+/cm^2. Inset shows details of transmisson peak.

Results

The effect of 3 MeV proton irradiation on R1 is shown in Fig. 1 for fluences up to $\Phi = 7x10^{14}$ H^+/cm^2. The points at which the peak and valley parameters were measured are indicated in the figure. Similar data for R2 are shown in Fig. 2. For both arrays, the effect of proton-induced disorder is small below fluences of about 10^{13} H^+/cm^2. The main effect at higher fluences is to reduce the sharpness of the features in the IV curves. For fluences above about $1x10^{14}$ H^+/cm^2, the peak current decreases noticeably and shifts to more negative voltages, while the valley current increases and shifts to less negative voltages. It is interesting to note that because of the combined effect of increasing I_v and decreasing I_p, there is an inflection point at about -0.5 V which is minimally affected by the irradiations.

Radiation-induced changes in the peak and valley currents are shown in Figs. 3 and 4 for arrays R1 and R2, respectively. For both arrays, the peak current decreases linearly with fluence:

$$I_p(\Phi) = I_p(0) - m\Phi \quad , \qquad (1)$$

where $I_p(0)$ = 2.25 and 15.2 μA and m = $2.6x10^{-15}$ and $2.2x10^{-14}$ $\mu Acm^2/H^+$ for arrays R1 and R2, respectively. For the valley current, a reasonable fit to the data is achieved using the form

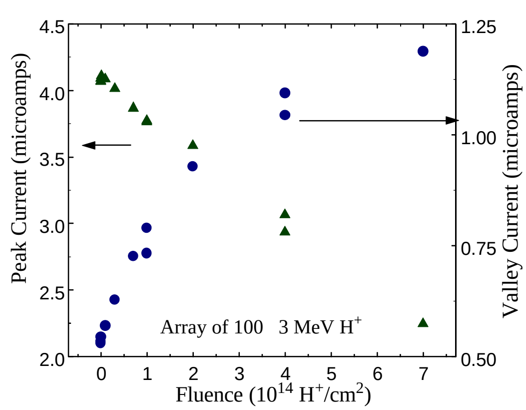

Fig. 3. Peak and valley currents in the array of 100 for various fluences.

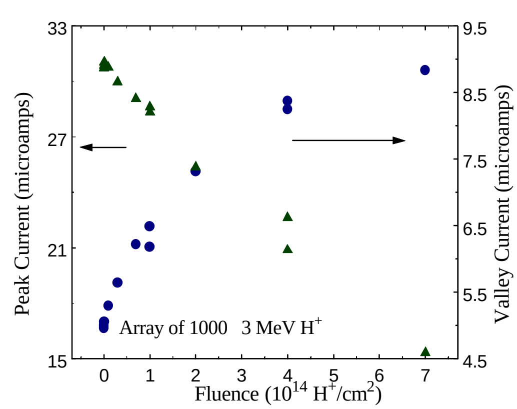

Fig. 4. Peak and valley currents in the array of 1000 for various fluences.

$$I_v(\Phi) - I_v(0) = (\Phi/a)^{1/2}, \qquad (2)$$

where $I_v(0) \approx 5\ \mu A$ and $0.53\ \mu A$, and $a \approx 4.9 \times 10^{13}\ H^+/cm^2\mu A^2$ and $1.7 \times 10^{14}\ H^+/cm^2\mu A^2$ for R1 and R2, respectively.

The peak-to-valley current ratio is shown for both arrays in Fig. 5. The solid lines in the figure represent an expression commonly used to describe the fluence-dependence of the maximum power in InGaAs photodiodes.[4] However, the simplest expectation for $I_p(\Phi)/I_v(\Phi)$, derived from dividing the functionalities of Eqs. (1) and (2), is also quite accurate for fluences up to about $1 \times 10^{14}\ H^+/cm^2$.

In Fig. 6, the ratio I_p/I_v is plotted as a function of time at room temperature following the last irradiation. The increase in I_p/I_v is logarithmic in time, as is the maximum power in the InGaAs diodes.[4] It can be seen that over a period of seven weeks, the value of I_p/I_v recovers almost 9% of its original value. Because of the self-annealing properties of these RTDs, a more extensive fitting of the current and voltage parameters than the simple ones given above was deemed inappropriate until further investigations can be made.

Discussion and Conclusion

One possible explanation for the changes in peak and valley currents observed here is that disorder introduces non-resonance leakage channels across the RTDs while broadening band edges and resonance widths, thereby ‘smearing’ the distinctive n-shaped IV curves of the RTDs. This effect is expected to cause peak currents to decrease, valley currents to increase and voltages to shift. If this damage mechanism is indeed appropriate for describing disorder-effects in the RTDs, it would be the first time outside the field of high temperature superconductivity that radiation-induced disorder has been seen to perturb quantum interactions in solid state electronics.

At the same time as disorder may be affecting quantum tunneling in the RTDs, there is evidence that the response of the RTDs is typical of many conventional (i.e., diffusive) majority carrier devices. As a general rule, displacement damage affects majority carrier devices by shortening the mean scattering time and length, increasing the diffusion coefficient, and gradually decreasing the carrier concentration. By contrast, disorder-effects in minority carrier devices arise mainly through the creation of unwanted trap and donor sites. An equivalent amount of

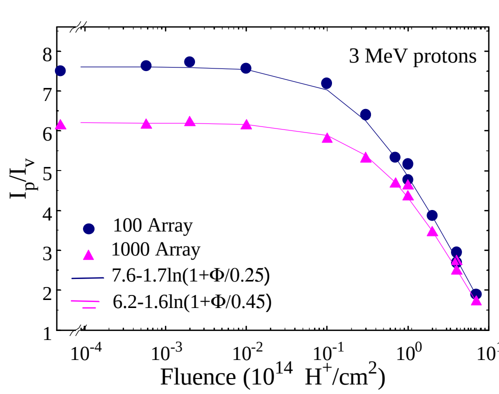

Fig. 5. Peak-to-valley current ratio for both arrays and various Φ. Lines: Fits to data, as shown.

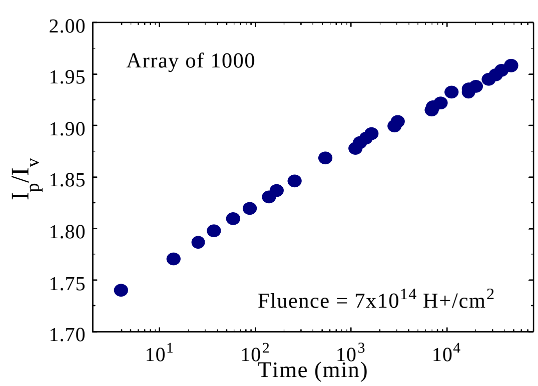

Fig. 6. Self-annealing of peak-to-valley current ratio.

damage affects the performance of minority carrier devices much more strongly than majority carrier devices.

One empirical method for examining how radiation damage changes the operating parameters in the RTDs is to compare the radiation tolerance of RTDs to that of conventional devices fabricated from similar and dissimilar materials. For example, in the InGaAs diodes fabricated on InP substrates, a dose equivalent to $4x10^{10}$ 3 MeV H^+/cm^2 causes the reverse current to increase by three orders of magnitude,[4] but in the RTDs a fluence of $4x10^{14}$ 3 MeV H^+/cm^2 increases the valley current by a factor of only 1.7. Hence, the RTDs appear to be orders of magnitude more tolerant to radiation damage than InGaAs photodiodes. Similar conclusions can be made using results on irradiated GaAs MESFETs.[5] As another example, the most radiation-tolerant photodiodes are based on InP quantum wells, which show incipient to moderate radiation-damage effects at fluences of 10^{11} - 10^{12} 3 MeV H^+/cm^2.[6] In comparison, the operating parameters of the RTDs show little change below about 10^{13} 3 MeV H^+/cm^2. Amorphous Si devices and some radiation-hardened majority carrier devices, on the other hand, are equally as tolerant to radiation damage as the RTDs measured here.[7]

The results presented above provide strong evidence that the RTDs possess a degree of radiation tolerance typical of majority carrier devices, yet simultaneously exhibit disorder-related effects unique to the quantum mechanical operation of the system. Further investigations are essential if the effects of radiation-induced disorder on RTDs are to be understood.

Acknowledgments

The authors gratefully acknowledge the contributions of Dr. Geoffrey P. Summers. This work was supported in part by the Office of Naval Research.

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